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R.A.R.D.E. MEMORANDUM 31/71

The detection of non-metallic anti-tank mines using sub-nanosecond pulse radar principles

Part I. Initial investigations
(title RESTRICTED)

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September, 1971

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3 The detection of non-metallic anti-tank mines using sub-nanosecond pulse radar principles (R)

Part I Initial investigations

(title RESTRICTED)

et al.

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Summary

This memorandum is a record of initial investigations carried out at RARDE in the period September 1968 to September 1970 into the use of ultrashort RF pulses for the detection of non-metallic mines. The background relating to the use of microwaves is considered and the requirements which must be met in applying this technique are discussed. Accounts of laboratory and field studies are given.

The investigation forms part of a pre-feasibility study being undertaken by RARDE into the problems of the detection of non-metallic land mines.

Approved for issue:

D.F. Runnicles, Principal Superintendent, 'E' Division

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1. INTRODUCTION

1.1 Background

The problem of detecting non-metallic mines has not yet been solved. Ideally one wishes to be able to identify the presence of explosive since this is the only component which is present to a greater or lesser extent in all mines. Such positive identification or detection of a mine can be carried out in theory by neutron irradiation or trace gas analysis techniques though their application is still in an early stage in the laboratory and will not be possible in the field until there is a significant advance in relevant technology. Moreover these techniques may not be viable under operational conditions.

An alternative approach to the problem is to examine the area which is suspected of being mined and seek information which after some processing will enable a decision to be made on the probability of a mine being present. The basic information which could be, for example, in the form of reflected electromagnetic radiation may not be uniquely associated with a mine and thus a decision process is necessary to reduce the number of spurious detection signals, or false alarms, which originate from natural phenomena.

Thus, if the depth below the surface of a buried object can be measured and found to be within the range normally associated with buried mines then the probability that the object is a mine is increased. If, in addition, information about the cross-sectional shape of the object in a plane parallel to the ground surface can be obtained (devices capable of measuring depth can readily be adapted to do this) and shown to be consistent with the shapes of known mines then the probability that the object is a mine is further increased.

To summarize therefore, the simultaneous acquisition of correct depth and shape information will not positively identify a mine nor will it distinguish between a real and a dummy mine, but, in theory, the majority of false detections should be eliminated.

Both depth and shape information can be obtained by the application of microwave techniques and their use as a possible solution to the problem of detecting mines has been investigated by E4 (Minewarfare) Branch, RARDE after a paper study (ref 1) carried out in 1968. Whilst their application is not considered likely to lead to a universal mine detector, that is to a device which is capable of detecting all mines in all environments, they could provide an instrument having a limited capability or form part of a system which employs more than one physical principle in the detection process. This latter concept, which could approach the requirements of a universal detector, might also employ infra-red techniques (to detect soil disturbances resulting from the laying operation) and perhaps one of a number of metal detecting methods.

1.2 Microwave Techniques in use in other Countries

Shortly after E4/RARDE had begun a study on the use of microwaves it was learned that a main line of investigation into the problem of the detection of non-metallic mines in the United States and the Federal Republic of Germany was concerned with the use of sub-nanosecond R.F. pulses. Some account of these investigations is given in references 2 and 3.

In view of the prior experience of both these countries in the application of microwaves to mine detection and, particularly, because of the much greater resources of US it was felt that UK should not enter into direct competition to try and produce an actual prototype microwave detector. It was therefore decided that UK work should concentrate on a full investigation and evaluation of the basic principles involved although active collaboration with US and FRG on their investigations would be maintained as far as possible. In addition any foreign detectors which became available would be fully assessed.

1.3 Purpose of Memorandum

This memorandum describes the initial investigations which have been carried out by RARDE into the use of RF pulse radar principles to measure the depth of burial of an object suspected of being a mine. The investigations cover both laboratory experiments and trials at the soil lanes facility established by RARDE at MVEE and therefore follow the first two phases of an idealised mine detection programme described in ref.4. This reference also contains details of the overall research facilities available for the programme.

2. SUB-NANOSECOND PULSE RADAR FOR NON METALLIC MINE DETECTION

2.1 Requirements for a Microwave Mine Detector

If measurement of depth using microwave techniques is to be valid for the purpose of detecting a mine then ideally the methods employed must be capable of resolving distances of 5cm in air (free space) though a resolution of 15cm could be tolerated for locating large anti-tank mines, such as the Russian TMDB mine, buried relatively deeply in a soil (clay) having a high dielectric constant.

The microwave radiation must obviously have sufficient energy to penetrate vegetation and about 30cm of soil. In addition the technique must be such that there is no mechanical contact with the ground as this would not only give rise to difficulties with thick vegetation and uneven ground but would result in a low sweep rate which is operationally unacceptable.

A resolution of 5cm by microwave pulse ranging implies a pulse width of 0.3 nanosecond (ns): correspondingly for a resolution of 15cm a 1ns pulse width is implied. Thus, of necessity, a sub-nanosecond pulse (SNP) radar is required and it follows immediately that the carrier frequency of the pulse must be considered.

It has been found, from past US work and UK study, that at

present the use of S-Band frequencies (1.7 - 5.2 GHz) is necessary in order to provide a reasonable compromise between the needs for adequate soil penetration, which decreases with increased microwave frequency, and the problems of designing microwave antennas of appropriate size which are able to produce narrow focussed beams, problems which, in the microwave mine detection context, become simpler with increasing frequency. A pulse width of 0.3ns at S band frequencies implies that a single cycle of a 3 GHz "carrier wave" is required: the maximum tolerable pulse of 1ns can be obtained from 3 consecutive cycles of the 3 GHz carrier wave or alternatively from a single cycle of a 1 GHz carrier wave. This is an over simplification of the position since the actual pulse is a wave packet at some particular repetition rate. A Fourier analysis is required to determine the precise range of frequencies involved and their relative importance. Such studies are being made but their results will not affect the basic argument that a single cycle pulse of approximately 0.3ns width is desirable.

2.2 Fulfillment of Requirements

The requirements can be met by the adaptation of standard microwave distance measuring techniques for which both frequency modulated continuous wave (FMCW) ranging and pulse ranging systems exist.

However though these conventional systems have been available for many years problems are encountered in the application of the techniques to mine detection. Conventional pulse ranging systems use R.F. pulses with widths of 0.1 s approximately, though a few high resolution radars with pulse widths of between 1 and 3ns have been developed in the last ten years, whilst conventional FMCW systems have resolutions of the order of a few metres which is equivalent to a pulse width of several nanoseconds. One US system used for feasibility studies (ref.5) is in fact a sub-nanosecond radar using a pulse length of 0.6ns. However this and other high resolution radars have used carrier frequencies at X-Band (5 - 12 GHz) and above. At these higher frequencies the problems of the generation of the microwaves and antenna design are relatively simple compared with those at S-Band.

The adaptation of FMCW techniques to mine detection presents a difficult practical proposition because it demands a large bandwidth (about 1 - 3 GHz) and a linear frequency sweep. Pulse radar systems, whilst still demanding a large bandwidth constitute a less severe electronic problem, though they are still very much in the research phase for the purposes of mine detection. UK effort has been concentrated on this latter technique.

2.3 Experimental Approach

It was obvious when the present investigations began that the first step would have to be the design and construction of a bread-board model SNP radar system to enable studies to be made of the many aspects of the detection of mines by microwaves that are not capable of theoretical assessment.

Prior to the development of such equipment a review was made of the circuitry required and the problems likely to be involved in its realization were assessed. The results are described in sections 2.4 to 2.6.

2.4 Generation of Sub-Nanosecond R.F. Pulses

2.4.1 Introduction

Several possible methods for the generation of short duration microwave pulses exist and their advantages and disadvantages for mine detection are reviewed below. Further information may be found from ref.6 and from the bibliography in Appendix 1.

2.4.2 Modulation of continuous microwave energy

Short pulses are obtainable by appropriately modulating a continuous wave. Modulators may be either of the transmission type where the amount of microwave energy passing through a two-part device is varied by reflecting some of the incident energy back to the source or by absorbing it, or they may be of the reflective type where the signal is amplitude modulated and the reflected energy separated from the incident energy in a one part system.

Modulation may be achieved through the transmissive mode with biassed microwave crystals and by varying the gain of travelling wave tubes. Reflective mode modulation is obtainable by varying the electron beam admittance of reflex klystrons. Ferrites can operate in either mode.

Full amplitude modulation is unobtainable through the transmissive mode which gives, typically, 10 to 15 dB modulation depth. The reflective mode in principle at least, is capable of full amplitude modulation but because of stability problems a maximum modulation depth of about 35 dB is generally obtained in practice though 80 dB has been achieved, but at the expense of pulse width.

The modulation frequency may be arranged so that the phase of the internal wave structure of each microwave pulse is the same with respect to the beginning of each pulse. This procedure is known as "phase locking" and the pulses are then said to be phase coherent.

In general pulse widths in the range 1 to 10ns are obtained by modulating continuous microwave energy. A few instances of the generation of sub-nanosecond pulses have been recorded, but such pulses have been generated with extreme difficulty and with low modulation. Experience has shown that a modulation depth in excess of 40 dB is necessary for the purposes of mine detection and as sufficiently short pulses cannot be generated at this depth by the modulation of continuous energy this method must be regarded as being of no practical value at present.

2.4.3 Shock-excited filter

This method is more useful than the previous one since sub-nanosecond pulses can be obtained through the use of a band-pass filter to suppress the unwanted frequencies in the Fourier spectrum produced by a baseband* pulse. The pulses are automatically phase locked.

Pulse widths of 0.2 to 1ns with peak powers between 0.5 and 10 watts have been generated at X-band frequencies using mechanical (eg. vibrating reed) and electronic (eg. tunnel diode) impulse generators with either active or passive filters.

The main disadvantage in the use of a shock excited filter is that relatively large quantities of energy are reflected along cables, etc, during the generation of the pulse and this gives rise to spurious pulses which must be discriminated against in any useful mine detector based upon this technique. The method was, however, briefly employed during the initial stages of the investigations.

2.4.4 Regeneration of feedback

In this method a short pulse of microwave energy is re-circulated through an amplifier and a non-linear element which sharpens the applied pulse. The characteristics of such a circuit however will not allow the phase locking which is vital to the use of an easy reception technique and this fact together with the general complexity of the method ruled out its use in the initial study.

2.4.5 Harmonic generation

Two techniques for the harmonic generation of microwave pulses exist. One is to drive a harmonic producing crystal into its operating region for short intervals: the other is to apply short RF pulses to a harmonic producing device with a filtered output. Both techniques are relatively complex with unknown performances for producing pulses suitable for mine detection and for these reasons they were not considered further.

2.4.6 Synthetic generation

The synthetic generation of sub-nanosecond pulses can be achieved in two ways. The first is through the synthesis of a large number of microwave carrier waves, a method which is being used in the US for research purposes. The requirements of extreme electronic stability with temperature variation, etc, and the interaction of the phase and amplitude modulation for each carrier wave means that the research equipment is complex and costly and this technique was therefore not considered further for use by E4/RARDE.

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*A definition of baseband pulse is given on page 11.

The second technique is to synthesize two suitable phase coherent base-band pulses. Because of its relative simplicity and potential for the purposes of mine detection it has provided the principal means of generating the sub-nanosecond pulses for the initial investigation.

The design of the equipment is described in Section 3.

2.5 <u>Antennas</u>

Apart from the actual generation of the pulses the major problem area in designing a sub-nanosecond pulse radar lies in the design of the component antennas because of the stringent requirements for bandwidth and directivity to produce a satisfactory performance. In addition the antennas have to operate in the near field region thus presenting further design problems.

It was realised from the outset that a lengthy and costly investigation would be necessary to design antennas whose performance was near optimum and that a reduced performance would have to be accepted for the purposes of initial investigations. The following antenna types were therefore considered to be suitable.

(a) Ridged waveguide horns (ref 9)

(b) Pyramidal horns modified by exponential flaring, or reduction of the waveguide height and by special waveguide co-axial transformers (including various impedance matching devices).

(c) Damped antennas in general including resistively damped horns and monopoles thereby broadening the antenna bandwidth but reducing gain.

Since the construction of ridged waveguide horns required more effort in terms of time and money than was available it was decided to concentrate on the other two types and the resulting antenna design is described in Section 3. It was, of course, recognised that the performance of the sub-nanosecond pulse radar would be limited but nevertheless it was expected that useful information would be obtained.

2.6 <u>Reception and Display</u>

Because a coherent pulse generator had been chosen, a commercial sampling oscilloscope has been used for the reception and display of the 0.3ns pulse. However it is recognised that this involves a visual display which may be unacceptable in the final design of a mine detector and further work on signal processing and data display will be required. This will not be started until the use of a sub-nanosecond pulse radar technique has been shown to be feasible for the detection of mines.

The sampling oscilloscope used is described in Section 3.

2.7 **Soil Attenuation**

Because the attenuation of microwaves in soil varies with frequency the pulse form will not be preserved. Dispersion will occur due to the greater attenuation of the higher frequency components in the pulse which is broadened as a consequence.

No attempt to study the effect of soil attenuation on the pulse shape has yet been made.

2.8 **Mine Target Characteristics**

Since the microwave pulse contains many frequencies the reflective properties of a buried mine will be complex. The initial study did not include any consideration of the pulse characteristics on the reflected signal but only attempted to detect buried mines.

3. LABORATORY STUDY

3.1 **Equipment**

3.1.1 **The synthetic generation of phase coherent sub-nanosecond microwave pulses**

Figure 1 gives a block diagram showing the basic generation of sub-nanosecond pulses. A 100 MHz oscillator of $\frac{1}{2}$ watt output power drives a step recovery diode module (type Hewlett Packard 33002A) and a pulse forming network.

The module contains the step recovery diode with its matching and biasing circuitry and is in co-axial form with 3mm sub-miniature type connectors. Further details of the module and of the operation of the step recovery diode are given in ref.7. When correctly loaded the output of the module is an impulse train, that is baseband pulses of width 0.15ns at a repetition rate of 100 MHz are generated. The amplitude of the pulse varies between 10 and 16 volts according to the quality of the step recovery diode.

Each pulse may be regarded as one half of a single cycle 3 GHz pulse. If each pulse is divided into two separate pulses with amplitudes approximately half that of the original pulse but still with the same width and one of the halves is inverted and delayed for 0.15ns and the two pulses then added together a single cycle 3 GHz pulse is formed. This process is carried out by the pulse forming network. A standard method of doing this is through the use of a shorted co-axial line and this has been adapted by G F Ross of Sperry Rand Research Center (USA) to operate at S-band frequencies with a 3.58mm (0.141in)diameter semi rigid co-axial cable. Further details of this network which was used during the investigation may be found in ref.10 and Fig.2 shows the pulse generated by this technique. The secondary pulse shown is caused by the initial pulse not being completely clean and it is thought that this is a function of the module rather than of the step recovery diode. The effect is still under investigation.

3.1.2 Antennas

Because circulators of sufficiently wide bandwidth were not available to allow the use of a single antenna for both transmission and reception of the microwave energy, a pair of antennas was used. Each antenna was a 40cm long pyramidal horn having a beam width of approximately 30° in the E plane and both were damped with a resistive coating of colloidal graphite to increase their band width. Towards the end of the experiments simple ridges were incorporated in the horns in an attempt to shorten the radiated pulse.

The antenna system has not been optimised and a detailed study is still required.

3.1.3 Reception

A Tektronix type 561B sampling oscilloscope with S-4, 3S2 and 3T2 plug in units was used. This gave an equivalent band width of DC to 14 GHz at 3 dB down and a time sensitivity of 0.02ns.

3.2 Performance of the Sub-Nanosecond Pulse Radar

The free space resolution was measured as 15cm. Sufficient signal to noise was obtained to allow the detection of 10cm square metal plates under at least 45cm of dry sand and under about 2 to 5cm of loam containing 20% moisture. Investigations were made in an anechoic chamber (ref 4) and included the detection of inert mines of various shapes and materials. An example of the detection of an inert mine in sand is shown in Fig.3. Inert mines were also detected in loam soil.

4. FIELD STUDY

4.1 Equipment

For the field study a US vehicle mounted metallic mine detector was modified to be a test rig for the equipment that had been used in the laboratory. This entailed the replacement of the metallic mine detection head with a boom to support the antennas, pulse generator and the S-4 head. The oscilloscope was mounted in the space normally occupied by the front passenger seat of the vehicle. Fig. 4 shows the equipment in position.

4.2 Trials

The equipment was tested at the RARDE soil lane facility (ref 4) established at MVEE (Christchurch).

Two types of inert filled anti-tank mines, the Soviet wooden box mine (TMDB) and the British light non metallic mine, were buried in the sand and clay lanes and in the adjacent sandy track and heathland.

In addition some plastic boxes of approximate dimensions 30cm (side or diameter) and 10 or 15cm thick were filled with dry sand and buried at the site.

4.3 Results

4.3.1 Introduction

The mines and plastic boxes were buried at depths typical for anti-tank mines but no attempt was made to measure absolutely the depth at which detection was achieved in any particular environment. Detection was defined as the observation of a recognisable additional pulse on the oscilloscope with the detection head over a mine when compared with the display obtained from the immediate surrounds of the mine. For recognition purposes the additional pulse had to have a minimum signal to noise ratio of 2:1 over the baseline noise (mainly caused by low level antenna ringing) and had to occur in the predicted position of the time axis of the display. For all the buried mines and objects employed the return pulse was separated from the ground return pulse except in the case of the heathland where the two pulses were adjacent.

The following results were obtained.

4.3.2 Sand lanes

Both types of mine and the plastic boxes were found at depths up to 30cm in sand which had several strata of different moisture content. The average moisture contents were between 5 and 10% by weight.

4.3.3 Clay lane

Detection was achieved at depths up to 7.5cm in the clay which contained 10% moisture and an example of an actual signature is shown in Fig.5. Phasing problems were encountered and further studies of these are necessary.

4.3.4 Sandy track

The mines were detected at depths up to 10cm in the relatively moist sand of 15% water content.

4.3.5 Heathland

A TMDB mine was buried under 5cm of soil with the vegetational cover being preserved. The mine was just detectable by interpreting the resulting pulse shape but, as expected, a clear signature was not obtained.

4.3.6 Asphalt lane

An additional test in which a large land mine was simulated by burying a concrete disc under the 10cm thick layer of asphalt was carried out. The disc which was 30cm in diameter and 20cm thick was horizontally emplaced at a depth of 5cm beneath the asphalt by tunnelling in from the

side of the lane, and the hole was then completely backfilled with the sand removed during the excavation. The concrete disc was detectable within the criteria stipulated in 4.3.1 but no attempt was made to vary size or position to obtain a change in reflected signal.

4.3.7 Surface laid and buried metallic mines

These were detected by position and amplitude information.

4.3.8 Detection Speeds

The speed at which detection of the mines was accomplished was generally about 1 metre per second though a 10cm square metal plate buried 15cm deep in sand was detected at 2.5 metres per second. The electrical detection signal was fairly uniform though gross changes produced by the different ground surfaces were obvious.

Mechanical test of the system showed that the equipment was capable of travelling at a speed of 10 metres per second on the asphalt road.

5. CONCLUSIONS

5.1 The investigations though limited in scope, have provided valuable information on the use of microwave pulse techniques to detect non-metallic mines.

5.2 The detection of some types of inert filled mines in various environments has been demonstrated.

5.3 Further studies are necessary, particularly in the design of suitable antennas, in the effects of soil attenuation, and mine characteristics and, at a later stage, in signal processing.

5.4 Research is still required to determine the precise limitations of the technique.

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Definition of Baseband Pulse

This is defined by American Standards Association (ref 6) as "In the process of modulation the frequency band occupied by the aggregate of the transmitted signals when first used to modulate a carrier. The term is commonly applied to cases where the ratio of the upper to the lower limit of the frequency band is large compared to unity. Examples are the bands employed for the transmission of picture and synchronising signals in television and for multichannel pulse telephone systems.

APPENDIX 1

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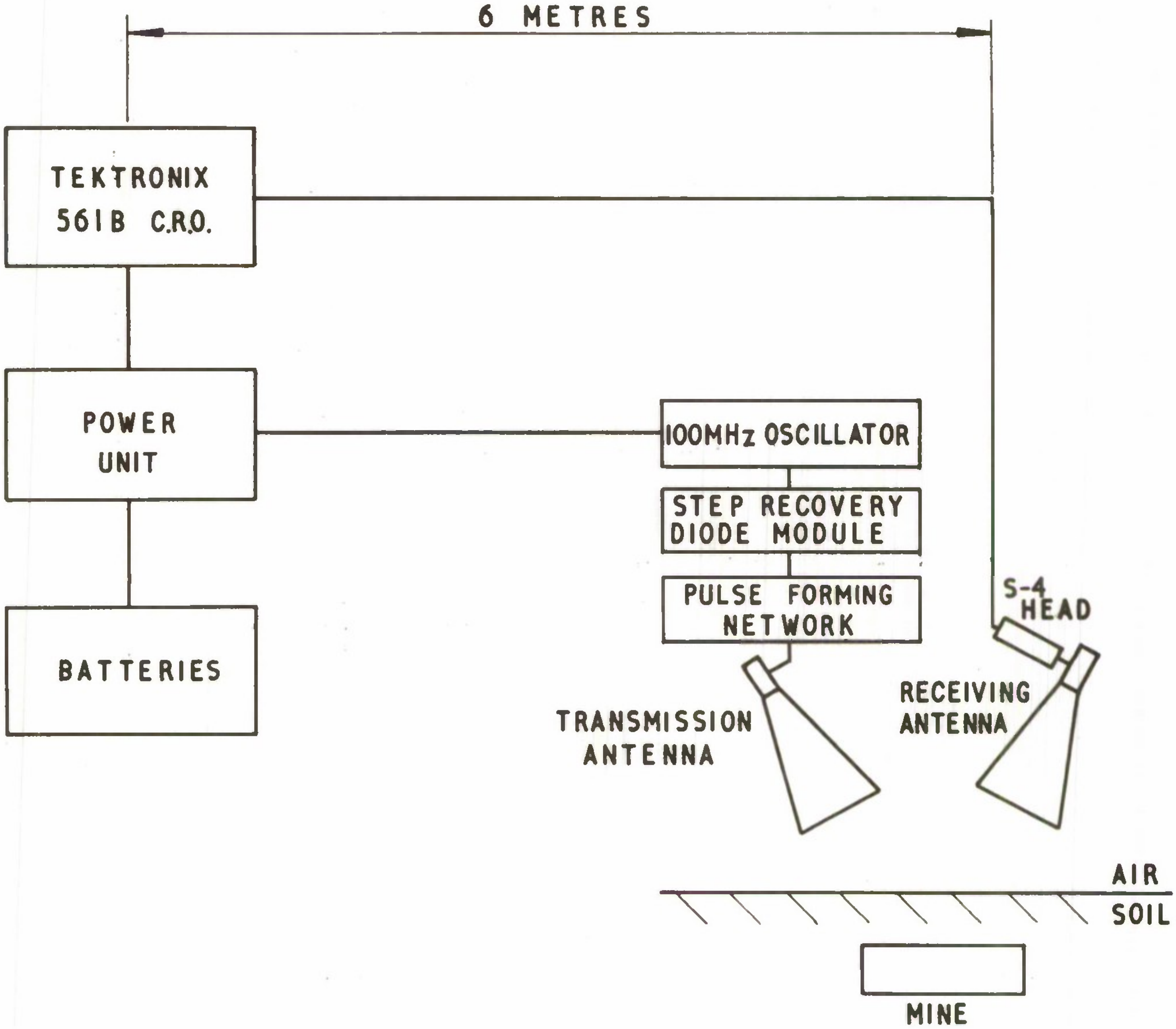

FIG I BLOCK DIAGRAM OF SUB-NANOSECOND PULSE RADAR

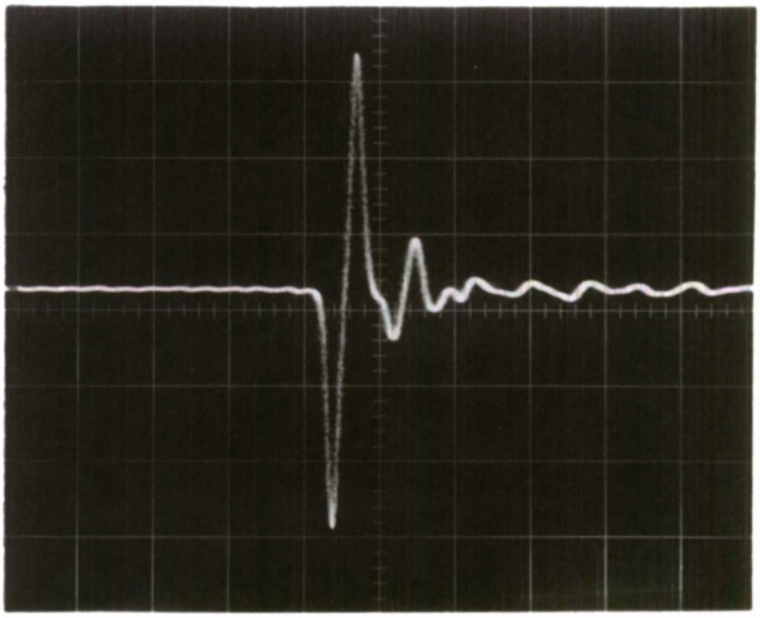

FIG 2 GENERATED PULSE (TIME AXIS: 0·5 nS per cm VERTICAL AXIS: PULSE AMPLITUDE OF 16 VOLTS PEAK TO PEAK ACROSS 50 OHMS)

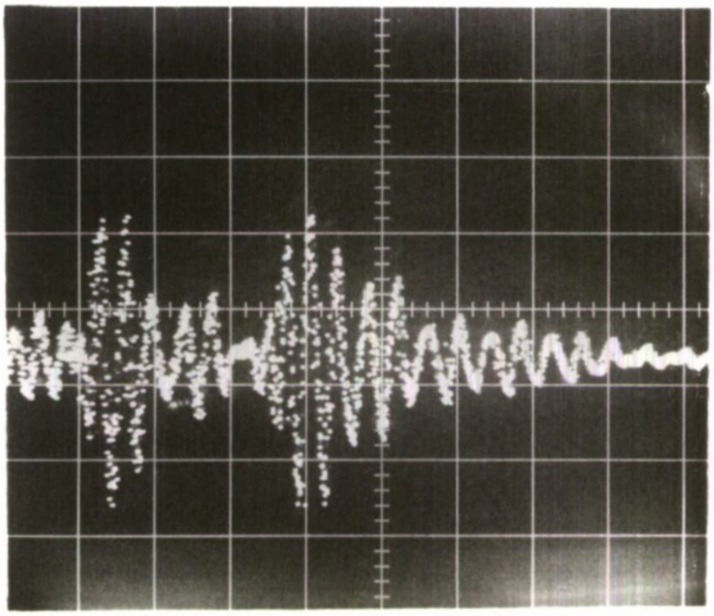

FIG 3 DETECTION SIGNAL OF AN INERT MINE BURIED IN DRY SAND.
LEFT HAND PULSE: SAND SURFACE RETURN
RIGHT HAND PULSE: MINE RETURN

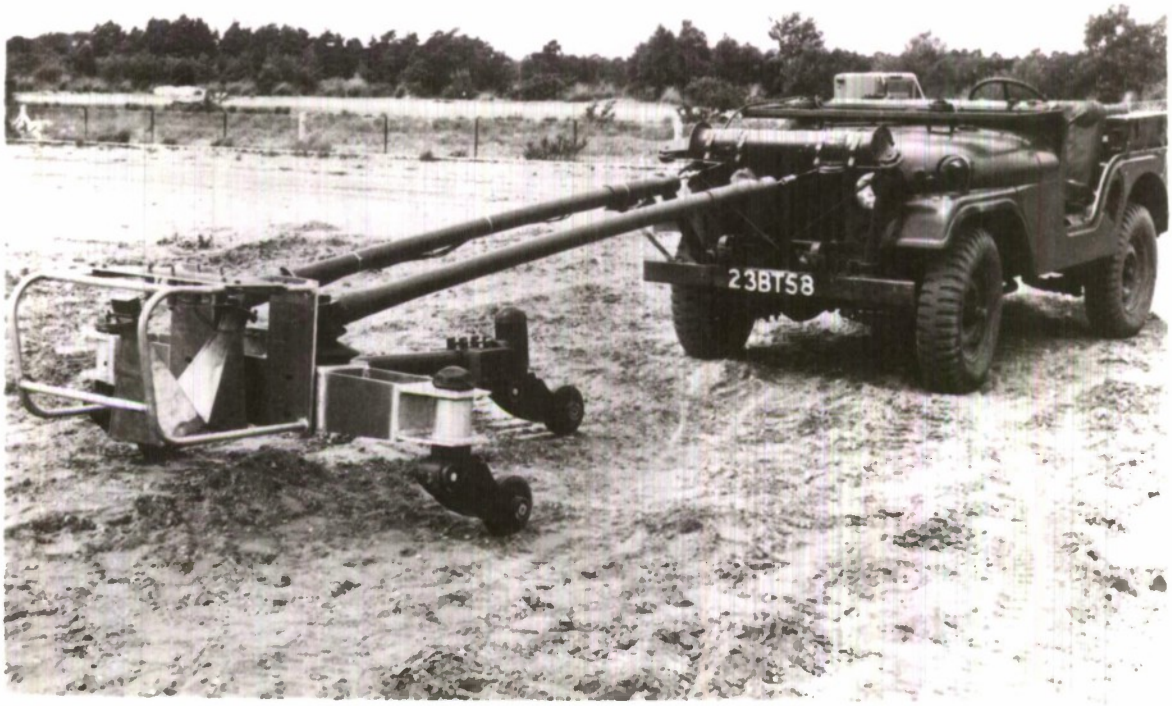

FIG 4 VIEW OF THE NON-METALLIC MINE DETECTION EQUIPMENT MOUNTED ON AN ADAPTED KAISER JEEP

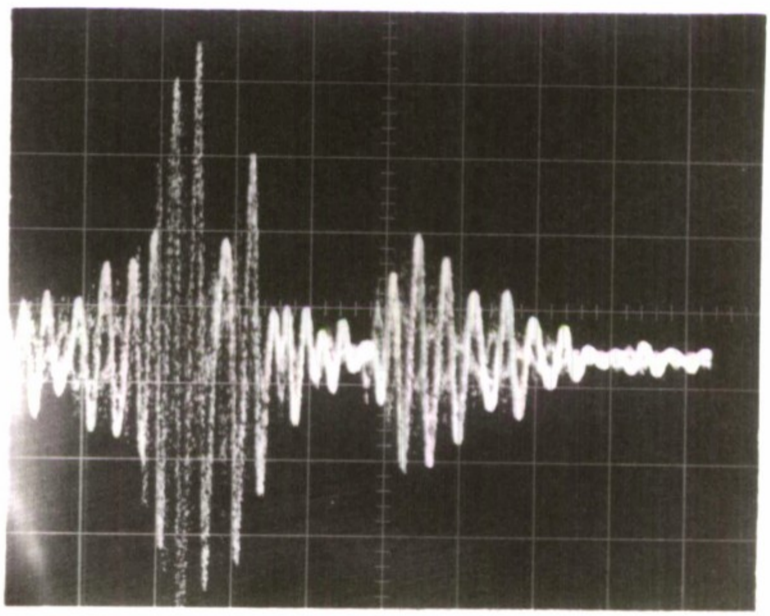

FIG 5 DETECTION SIGNAL OF AN INERT TMDB MINE BURIED UNDER 7·5 cm OF CLAY SOIL.

LEFT HAND PULSE: GROUND SURFACE RETURN

RIGHT HAND PULSE: MINE RETURN

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